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Physics

The Study of Angular Distributions of ®⁻-Mesons in (p, d, He, C)(C, Ta) Collisions at 4.2 and 10 AGeV/c Momenta

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ABSTRACT. The degree of anisotropy of ®⁻ mesons emission can be more directly determined by studying the angular distributions in the CMS of colliding nuclei. From the analysis of angular distributions of ®⁻ -mesons the anisotropy coefficient ~ for (p, d, He, C)-(C, Ta) (4.2 and 10 AGeV/c) collisions was obtained. The anisotropy coefficient is similar for the symmetric (or approximately symmetric, A_P ùA_T) systems of nuclei and increases slowly with mass numbers of projectile (A_P) and target (A_T) for other systems. At small multiplicities of pions ($n_{®J:}$á < $n_{®-}$ >) the degree of anisotropy is greater than at high multiplicities ($n_{®-}$ > < $n_{®-}$ >). The decrease of the parameter ~ for more central events ($n_{®-}$ > < $n_{®-}$ >) indicates that the angular distributions of pions become more isotropic at small impact parameters (b ì 0). The anisotropy coefficient ~ increases linearly with the kinetic energy E^*/ E_{max}^* (E_{max}^* is the m6ximum available kinetic energy in the CMS) and up to 100 MeV, the pions are emitted isotropically (parallel spectra) for almost all systems. Our results agree with the predictions of the intranuclear cascade models. The data obtained from the propane bubble chamber (PBC-500) system utilized at JINR. The qualitative agreement of our experimental results with the predictions of the quark gluon string and the ultrarelativistic quantum molecular dynamics models (QGSM, UrQMD) was observed.
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Key words: multiparticle azimuthal correlations, collision, nucleus, proton, pion

The quest to use energetic heavy ion collisions to infer properties of infinite nuclear matter, such as the equation of state (EOS) under conditions of density (or pressure) and temperature significantly different from the ground state conditions has proven to be a difficult task, although an impressive amount of data was obtained using experimental setups of increasing sophistication. In particular, the mean free paths of pions [1], the most abundantly created particles, with momenta below 1 GeV/c are neither large nor small compared to typical nuclear sizes. Therefore methods of analysis resting on the validity of either of these two extremes in the hope to simplify the theoretical description are bound to lead only to qualitative success at best.

An important lesson that was learned in the last two decades was that definite conclusions on nuclear matter properties based on a single observable had proven to be premature and/or of limited accuracy, aside from not being sufficiently convincing. As an example, original hopes [2], to use deficits in pion production relative to expectations based on compression-free scenarios were not supported by transport theoretical simulations [3]. On the other hand, transport calculations [4] showed that pion azimuthal correlations, 'flow', qualify as an observable that could contribute significant constraints on the EOS.

Our previous results on pion production experiment (cross sections, multiplicities' rapidities, transverse momenta, intercorrelations between various characteristics, etc) using the streamer chamber spectrometer SKM-200 in inelastic and central nucleus-nucleus interactions are published in [5-8]. It was shown that these particles are produced mainly in independent nucleon-nucleon (NN) collisions. The aim of the present work is to present a more complete systematics of highly differential pion emission in heavy ion reactions obtained with the **(PBC-500)** device, varying the incident energy (from 3.7 to 10 A GeV), the system's size (from $A_P + A_T = 4 + 12$ to 12+181, where A_P and A_T, are the projectile and target mass number, respectively), in hadron-nucleus system's p(C, Ta) and a new detailed analysis of the π^- meson angular distributions in these interactions. Moreover, the degree of anisotropy in pion emission from the analysis of angular distributions were determined and provided for comparison at the different energies. The dependence of the anisotopy coefficient α on the projectile (A_P) and target (A_T) nucleus were investigated.

Experimental Data

The data were obtained from Propane Bubble Chamber systems (PBC-500) utilized at JINR.

The 2 meter long Propane Bubble Chamber (PBC-500) was placed in the magnetic field of 1.5 T.

The procedures for separating out the pC, ^{2}HC, He C collisions in propane (C3H8) and the processing of the data including particle identification and corrections are described in detail in Ref. [9]. The analysis produced 4581 events of ^{2}H C, 1424 of ^{2}HTa, 9737 of HeC, 1532 of HeTa (at an energy of 3.4 GeV/nucleon), 5882 and 16509 events of pC interactions at the momenta of 4.2 and 10 GeV/c, respectively, and 2342 events of pTa (at 10 GeV/c) collisions.

The protons with momentum $p < 150$MeV/c were not detected within the PBC-500 as far as their track lengths are less than 2mm (pC interactions), and protons with $p < 200$MeV/c were absorbed in the Ta target plate (the detector biases). Thus, the protons with momentum larger than 150MeV/c were registered in pC interactions, and the protons with $p \geq 250$MeV/c in pTa collisions. In the experiment, the projectile fragmentation products were identified as those characterized by the momentum $p > 3.5$ GeV/c (4.2, 4.5 GeV/c/N) or $p > 7$ GeV/c (10 GeV/c/N) and angle $\Theta < 3.5°$, and the target fragmentation products - by the momentum $p < 0.25$ GeV/c in the target rest frame. The latter ones are mainly evaporated protons. After these selection criterions, the remaining protons are the participant protons. For the analysis minimum three particles $N_{particles} \geq 3$ were required for the reliable determination of the correlation coefficients.

The analysis of ®¯ meson angular distributions

In our experiment a detailed analysis of π^- meson production in a wide range of interacting nuclei with masses A_P (4-24), A_T (6-207) [5, 6] and interesting investigation about the mechanism of pion production was performed from the analysis of angular distributions [7, 8].

The degree of anisotropy in pion emission can be more directly determined by studying the angular distributions in the CMS of colliding nuclei. Our aim was to study $\cos\Theta^*$ distributions of π^- mesons in A_P

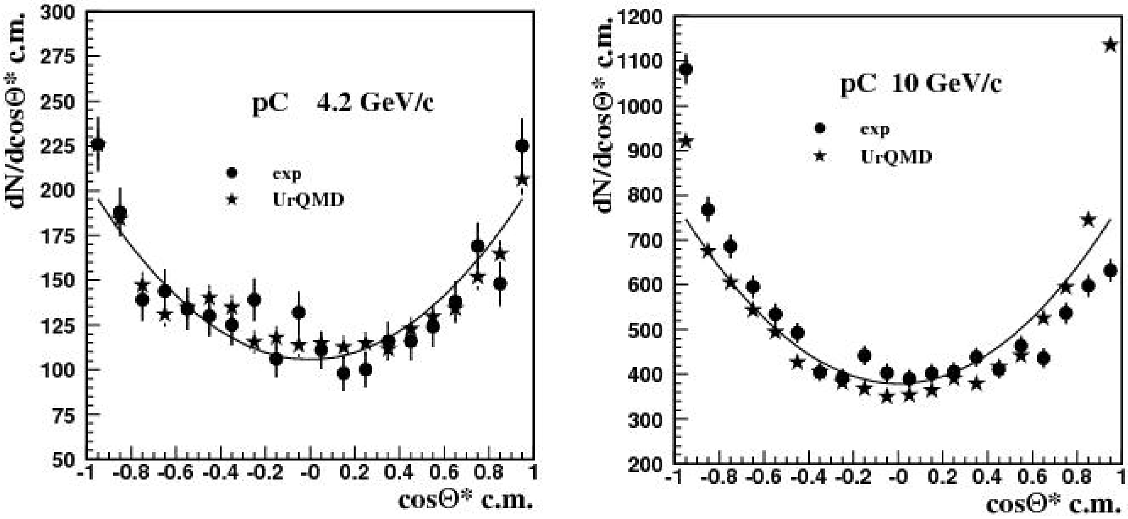

Fig. 1. cosΘ* distributions (in the CMS) of π^--mesons in experimental (õ) and UrQMD generated (★) pC (4.2 and 10 GeV/c) collisions. The curves are the result of an approximation using equation (1).

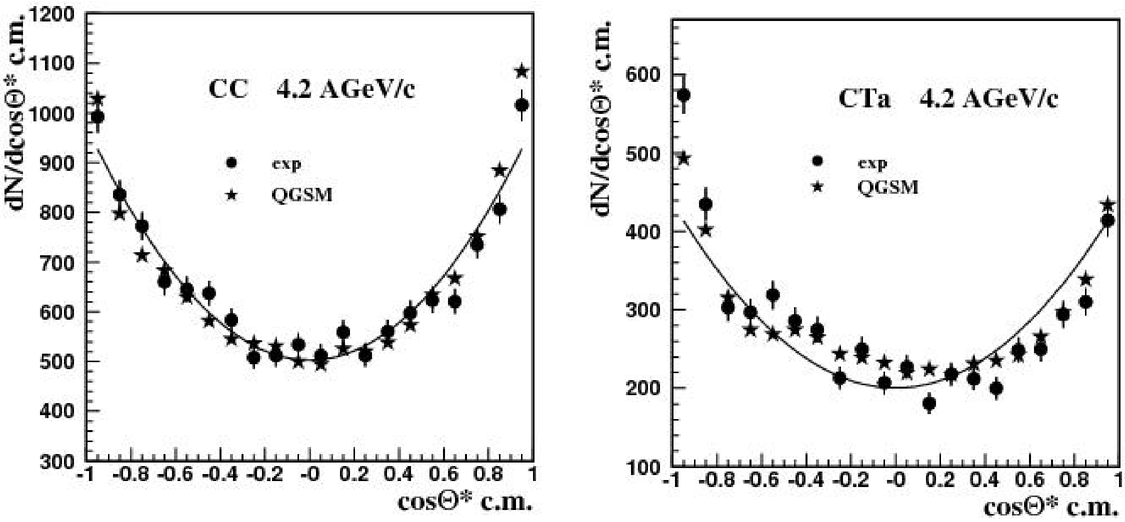

Fig. 2. cosΘ* distributions (in the CMS) of π^--mesons in experimental (õ) and QGSM generated (★) C(C, Ta) (4.2 A GeV/c) collisions. The curves are the result of an approximation using equation (1).

(p, d, He, C) A_T (C, Ta) interactions (Θ^* is the emission angle in the CMS of colliding nuclei). The experimental distributions we have approximated by the ansatz [10]:

$$dN/d\cos\Theta^* = \mathrm{const}(1+\alpha\cos^2\Theta^*)\,, \qquad (1)$$

were α is the anisotropy coefficient. The studied cosΘ* distributions of π^- mesons in experimental and generated **(QGSM, UrQMD)** p-C (4.2 and 10 GeV/c), C(C, Ta) (4.2 AGeV /c) interactions are presented on Figs. 1, 2. In Table 1 the results of approximation by (1) for various pairs of nuclei are listed. One can see (Table 1), the parameter α is similar for symmetric (or approximately symmetric, $A_P \approx A_T$) systems of nuclei and increases slowly with mass numbers of projectile (A_P) and target (A_T) for other systems. That may be the result of asymmetry of the colliding interactions.

The dependence of α on kinetic energy E^*/E_{max}^* (E_{max}^* is the maximum available kinetic energy). nuclei system (A_P « A_T). For NN $\rightarrow$ NNπ^- the parameter is greater than 3 [10]. The nucleus-nucleus collisions thus provide a more isotropic source of pions at these energies, than in the nucleon - nucleus energy) in CMS, was studied (Table 1.). It is shown that the anisotropy coefficient increases linearly with E^*/E_{max}^*. Up to 100 MeV,

Table 1. The number of events and ®¯-mesons, the anizotropy coefficient ~ of ®¯-mesons in verious range of multiplicities and of E*-kinetic energy in pC (4.2 and 10 GeV/c), (d, He, C) (C, Ta) (4.2 A GeV/c) and pTa (10 GeV/c) experimental and generated collisions (the result of the approximation of cosn* distributions using equation (1), see text)

$A_P + A_T$		N_{even} / N_{pion}	α=	α ¼ f(E*)		
				0.05 áE*Y0.20	**0.02áE*Y0.44**	**0.45á E* Y0.08**
pC 4.2გევ/c	**exp.**	5882 /4698	0.94±0.11	0.45±0.13	1.50±0.25	1.96±0.58
	UrQMD	16143 /13500	0.84±0.06	0.30±0.08	0.93±0.11	2.48±0.34
pC 10გევ/c	**exp.**	16509 /17362	1.07±0.06	0.17±0.06	1.12±0.11	4.00±0.44
	UrQMD	50191/30676	1.77±0.05	0.60±0.05	1.73±0.08	4.63±0.31
dC	**exp.**	4581 /3452	0.71±0.09	0.45±0.15	1.43±0.23	3.35±1.32
	UrQMD	27502 /23210	1.05±0.04	0.24±0.04	1.23±0.08	3.33±0.25
HeC	**exp.**	9739 /2898	0.82±0.07	0.50±0.11	1.32±0.16	4.13±1.20
	UrQMD	31716 / 37790	1.04±0.04	0.17±0.04	1.42±0.10	4.01±0.31
CC	**exp.**	15962 /25410	0.94±0.05	0.32±0.05	1.20±0.11	2.62±0.32
	QGSM	50000/85030	1.07±0.02	0.33±0.02	1.73±0.05	3.83±0.22
pTa	**exp.**	2342 /3147	1.33±0.13	0.57±0.14	1.57±0.28	2.40±0.61
	UrQMD	7230 / 12238	1.36±0.07	0.48±0.07	0.71±0.17	2.31±0.21
(d,He)Ta	**exp.**	2956 /3337	0.94±0.11	0.64±0.13	1.46±0.27	1.77±0.66
	UrQMD	17629/29886	0.96±0.04	1.05±0.04	0.74±0.06	1.27±0.21
CTa	**exp.**	2469 /6092	1.18±0.09	0.82±0.11	2.01±0.26	2.49±0.59
	QGSM	9130 /48110	0.99±0.03	0.48±0.03	1.44±0.12	1.51±0.07

the pions are emitted isotropically for almost all systems and the decrease of the anisotropy parameter may be caused by an increase in the number of NN collisions. Low-energy pions might be emitted at a later stage of collisions than highly energetic ones [11]. The slope is similar for light, symmetric pairs and the asymmetric, heavier systems. For the heaviest pairs of nuclei (CTa) the slope is larger.

The dependence of the parameter α on kinetic energy E^* in the CMS in central ArKCl collisions at a momentum of 2.6 GeV/c per incident nucleon for π^--mesons was studied at the Berkeley streamer chamber [12] and the value α=0.52. In this experiment α increases with E^*, achieves its maximum and then decreases [12, Fig. 1]. Meanwhile, the calculations carried out within the framework of the Cugnon intranuclear cascade model [13] for their data, predicts the increase of α with E^*. Our result is that the linear increase of α with E^*/E_{max}^* agrees qualitatively with the prediction of the Cugnon model.

We divided the initial events into two subsamples: 1) $n_{\pi^-} \leq < n_{\pi^-} >$, the events in which the π^--mesons multiplicity n_{π^-} is less than the average multiplicity $< n_{\pi^-} >$; 2) $n_{\pi^-} > < n_{\pi^-} >$, the fraction of the events in which ~ 40% for all pairs of nuclei. We analysed these two groups of events and obtained the anisotropy parameter for them. The second group of events, which corresponds to more central interactions, the parameter α is smaller than for the first group. The decrease of α for the events with $n_{\pi^-} > < n_{\pi^-} >$ indicates that the angular distributions of pions become more isotropic for more central collisions (small impact parameter).

The Dubna intranuclear cascade model assumes that a nucleus-nucleus interaction consists of a series of subsequent hadron-hadron collisions. Each of the colliding nuclei is treated as a gas of nucleons moving within a potential well, i.e. nucleons are bound within a nucleus. The distribution of the nucleon density, kinematics of Δ isobar formation (but not the dynamics of their subsequent interactions,

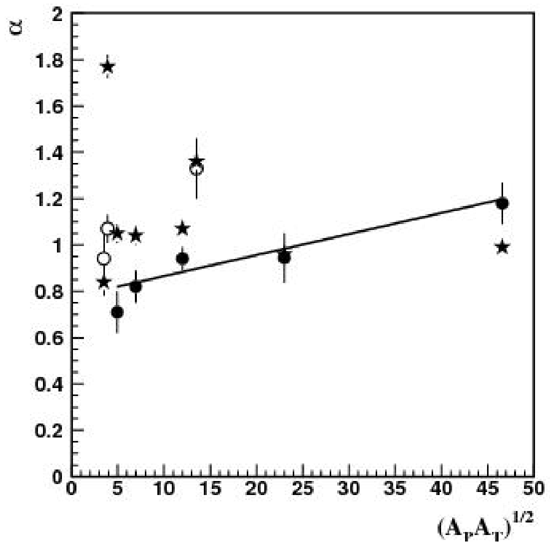

Fig. 3. The dependence of the anisotropy coefficient on the $(\mathbf{A_P * A_T})^{1/2}$ for π^- mesons in experimental **(o)** - pC (4.2 and 10 GeV/c), pTa (10 GeV /c), **(õ)** - (d, He, C)(C, Ta) (4.2 AGeV /c) and **(★)** - generated (UrQMD, QGSM) interactions. The lines are the result of the linear approximation of the data.

i.e. it is assumed that isobars decay instantaneously within the nucleus), and absorbtion of pions by pairs of nucleons are taken into account. Thus, we can conclude that our results qualitatively agree with the predictions of the Dubna intranuclear cascade model.

In order to increase the accuracy of the results obtained in these collisions, we also studied the behavior of the anisotropy coefficient generated collisions. Several theoretical models were proposed for nucleus-nucleus collisions at high energy. We used the Quark Gluon String Model (QGSM) [14, 15] and Ultra-relativistic Quantum Molecular Dynamics Model (UrQMDM) [16-18] for comparison with experimental data. The QGSM is based on the Regge and string phenomenology of particle production in inelastic binary hadron collisions. The UrQMD model is now widely applied for simulations of particle production and flow effects in various nucleus-nucleus interactions [19, 20], although its original design was directed towards high energies. We generated CC (2.65 fm) and CTa (6.53 fm) interactions by QGSM and dC (2.79 fm), HeC (2.79 fm), dTa (5.31 fm) and HeTa (5.46 fm) interactions by UrQMDM, as well as 50000 events for dC, HeC, CC, CTa and 1000 events for dTa, HeTa collisions, respectively.

One can see $\cos\Theta^*$ distributions (Figs. 1-3) of π^- mesons in A_P (p, d, He, C)-A_T (C, Ta) interactions for experimental and generated (QGSM, UrQMD) events i.e the degree of anisotropy within errors in pion emission are in good agreement with each other (Table 1).

Conclusion

The analysis of $\cos\Theta^*$ angular distributions of π^--mesons in experimental and generated **(QGSM, UrQMD)** pC (4.2 and 10 GeV/c), pTa (10 GeV /c), (d, He, C) (C, Ta) (4.2 AGeV/c) collisions were carried out. The pC system is the lightest studied one, and the pTa is extremely asymmetrical system in which differential transverse flow of protons and pions have ever been detected for these particles. The dependence of α on kinetic energy in CMS, on multiplicity of pions and on the mass numbers of projectile (A_P) and target (A_T) for all interactions were studied:

1. The anisotropy coefficient increses with E^*/E_{max}^* and up to 100 MeV, the pions are emitted isotropically for almost all systems;

2. At small multiplicities of pions (**n**$_{®–}$ á < **n**$_{®–}$ >) the degree of anisotropy is greather than at high multiplicities (**n**$_{®–}$ > < **n**$_{®–}$ >), i.e. the angular distributions of pions become more isotropic for more central events (at small impact parameters, $b \to 0$).

3. The anisotropy coefficient is similar for the symmetric (or approximately symmetric, $A_P \approx A_T$) systems of nuclei and increases slowly with mass numbers of projectile (A_P) and target (A_T) for other systems.

4. The QGSM and UrQMDM satisfactorily describe the $\cos\Theta^*$ angular distributions of π^--mesons for all systems.

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ფიზიკა

®$^-$ -მეზონების კუთხური განაწილებების შესწავლა (p, d, He, C)-(C, Ta) დაჯახებებში 4,2 და 10 AGeV/c იმპულსის დროს

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®$^-$ -მეზონების გამოსხივების ანიზოტროპიულობა შესწავლილ იქნა უშუალოდ მათი კუთხური განაწილებებიდან ურთიერთქმედი წყვილების მასათა ცენტრის სისტემაში (მ.ც.ს.). ამდენად, (p, d, He, C) (C, Ta) (4,2 და 10 AGeV/c) დაჯახებებში ®$^-$-მეზონების კუთხური განაწილებებიდან დადგენილ იქნა ~ ანიზოტროპიის კოეფიციენტი. მიღებულ იქნა, რომ ~ ანიზოტროპიის კოეფიციენ-ტი ერთნაირია სიმეტრიული სისტემებისათვის (ან მიახლოებით სიმეტრიული, A_P ÙA$_T$) და მდოვრედ იზრდება დამჯახებელი წყვილების დამცემი (A_P) და სამიზნე (A_T) მასური რიცხვების გაზრდისას. მცირე მრავლობითობის ($n_{®J}$= á < $n_{®J}$ >) მქონე პიონებისთვის ანიზოტროპიის კოე-ფიციენტი ~ მეტია, ვიდრე შედარებითი დიდი მრავლობითობის ($n_{®J}$ > < $n_{®J}$ >) მქონე პიონებისთვის. ~ პარამეტრის შემცირება შედარებით ცენტრალურ არეში ($n_{®J}$ > < $n_{®J}$ >) მიუთითებს ®$^-$-მეზონების კუთხური განაწილებების იზოტროპიულობაზე დაჯახების პარამეტრის შემცირებისას (b ì 0). ანიზოტროპიის კოეფიციენტი იზრდება თითქმის წრფივად კინეტიკური ენერგიის გაზრდისას E^*/E_{max}^* (E_{max}^* არის შესაძლო მაქსიმალური კინეტიკური ენერგია მასათა ცენტრის სისტემაში) და 100 მევ-ის შემდეგ ®$^-$-მეზონების გამოსხივება ერთნაირია ყველა ურთიერთქმედი წყვილისთვის (სპექტრების პარალელობა). ჩვენი შედეგები თანხმობაშია შიდა ბირთვული კასკადური მოდელების წინასწარმეტყველებასთან. ექსპერიმენტული მასალა მიღებულია ბირთვული კვლევების გაერთია-ნებული ინსტიტუტის (JINR) მაღალი ენერგიების ლაბორატორიაში ფილმური დეტექტორის (პროპანის ორმეტრიანი ბუშტოვანი კამერა - PBC-500) საშუალებით. კვარკ გლუონური სიმური და ულტრა რელატივისტური კვანტურ მოლეკულურ დინამიკური მოდელები (QGSM და UrQMD) ცდომილების ფარგლებში დამაკმაყოფილებლად აღწერენ ექსპერიმენტულ შედეგებს.

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